Mechanical Design of Radiation Shielding for NSLS-II

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MEDSI 2014 Australian Synchrotron

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Introduction

Radiation shielding of the NSLS-II facility is provided by bulk shielding, consisting of thick concrete walls and earth berms, and numerous supplemental shield assemblies. A structured organization was created to enable iterative interaction between physicists and engineers to overcome various design constraints, for the purpose of final safety approval. Examples of challenging shielding configurations and their mechanical designs are presented.

Physics – Acquiring Specifications and Requirements

High energy radiation, generated by accelerators, can cause ionization of the atoms in material, which for human tissue will cause damage to the complex biological molecules necessary for the function of life. Shield materials, such as lead, concrete, iron, earth, high density polyethylene and aluminum, attenuate the radiation fields to safe levels, by absorbing the energy in inert material. This spares the accelerator staff and users from the risk of high level radiation dose exposure.

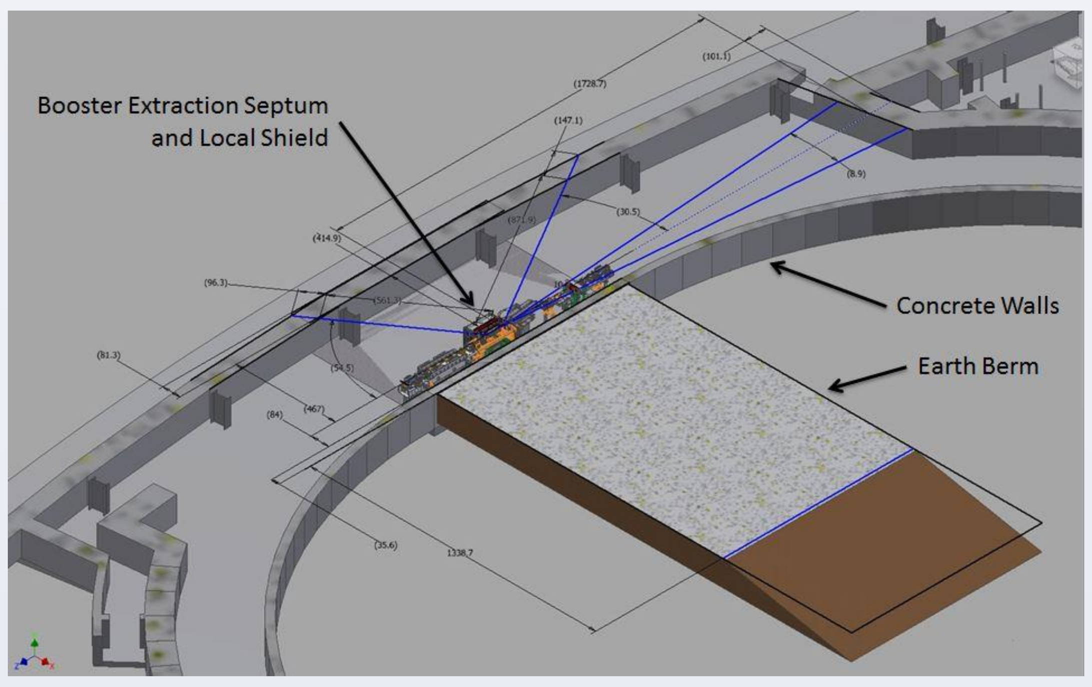


Fig. 1. Beam plane cut view of the shielded Booster Extraction Septum, showing trace lines from source point through the supplemental, also called local, and bulk shields.

The building and berm attenuate the radiation through their bulk shield walls. The equation used to determine each of their wall thicknesses was [1]:

$$H = \sum\{(F_i \times J/R^2)\} * e^{-(t/\lambda i)} \qquad \text{Dose Rate in mrem/hr} \qquad (1)$$

The radiation source term, F_i, of particle components (i = gamma, low and high energy neutrons) is generated from an assumed beam power loss, J (in kWatts), hitting a thick target (i.e., 30 cm of copper or steel) along the beam axis. The dose rate is calculated, transverse to the beam axis at a distance, R, from the target, after passing through a thickness, t, of shielding material, with attenuation length, λ_i. The total dose rate is the sum of the terms. For NSLS-II, the storage ring concrete walls, typically 100 cm thick, were calculated to attenuate radiation to dose levels < 0.5 mrem/hr at the surface of the outer wall, for an assumed operational beam loss rate of 1.1 nC/min for 3 GeV beam in the storage ring magnets.

Operational losses greater than the assumed J levels for the bulk shield are additionally attenuated with local shields near the loss point. An example of an Operational Loss (OL) shield is a Beam Dump (see fig. 7). Steering Error Loss (SEL) and Beam Scatter Loss (BSL) are abnormal losses, which also require attenuation with local shields. The equation to determine the maximum steering angle, Θ_M, for a dipole magnet is [2]:

$$\Theta_M(\text{rad}) = 2\cdot\sin^{-1}\left[\frac{B_M(T)\cdot L_m\cdot 0.29979}{2\cdot P_m(GeV/c)}\right] \qquad \text{Max Angle for a Dipole} \qquad (2)$$

Where B_M is the maximum magnetic field, P_m is the minimum beam momentum, and L_m is the magnetic length. If Θ_M exceeds critical value, dose levels outside the shield wall require additional evaluation.

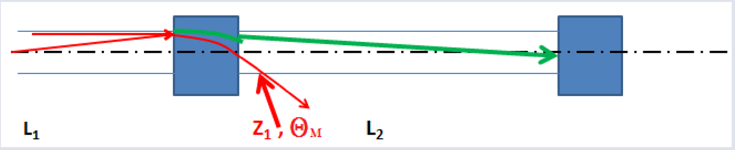


Fig. 2. Steering Angle, Θ_M, of Electron Beam by Dipole Magnet

SEL shields are defined where the entire beam current can be steered out of the beam pipe and not hit any significant amount of material before hitting the bulk shield wall. Examples of local shields for this purpose are the Dipole Shadow Shields (see fig. 5) and the Septum Shields (see figs. 3 & 6), where the injection septum is off, causing the injected beam to hit the septum vacuum chamber wall. BSL shields are defined where a significant portion of the beam is scattered before it hits the bulk shield wall. Beam hits material inserted into its path and it diffuses, causing a shower to be initiated, but without enough thickness to be considered as a thick target. An example of a BSL is the SR Scraper Shield (see fig. 8), where beam scrapes material, causing a shower for measurement by the Loss Control Monitoring system. Another example of a BSL is The Ratchet Wall Collimator Shield (see fig. 9).

Dose rates, for radiation propagating through SEL and BSL shields, were calculated using the Monte-Carlo radiation transport code FLUKA. If estimates exceeded those permitted for the occupied space, local shield designs were expanded, to reduce levels. For the SR injection septum, models showed high values of dose on the experimental floor, so its length was extended and additional concrete was added, to reduce the neutron component of the dose to acceptable levels.

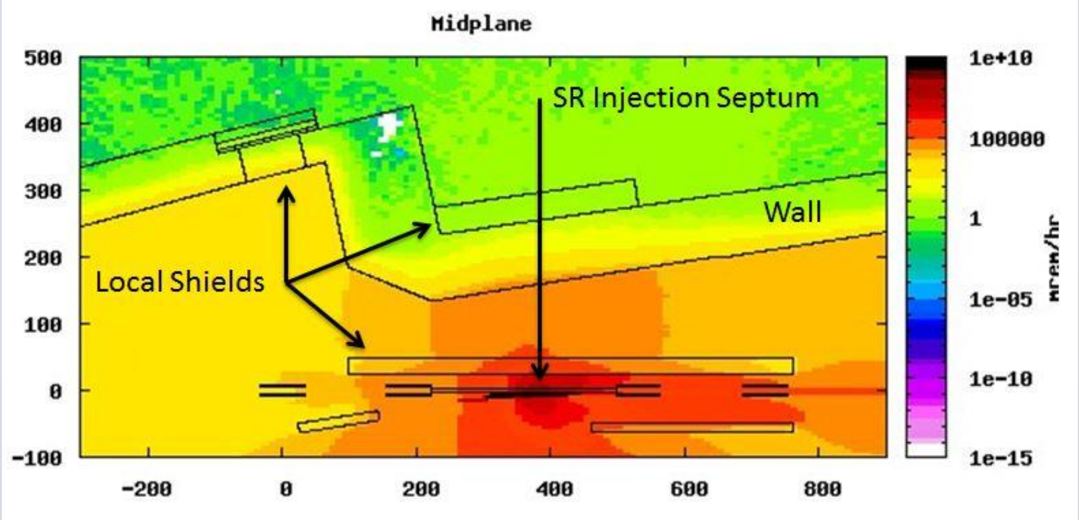


Fig. 3. FLUKA analysis model of the SEL's for the injection beam hitting the SR Injection Septum, when it trips off

Coordination – An Iterative Process

Coordinating information and sharing design intentions between many special disciplines was accomplished by establishing three meeting groups, Local Shield Design Coordination, Installation, and Shield Assembly and Quality Control. It enabled interactions for design concepts, through to the completed installation of certified shields.

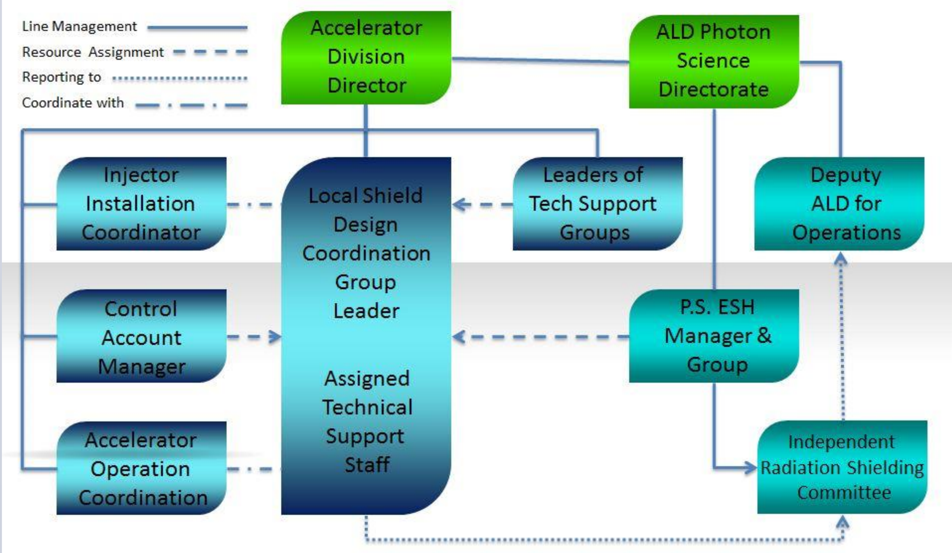


Fig. 4. Line management for the NSLS-II Shield System project

Benefits of LSDCG meetings included:

- Layout reviews identified radiation controlled areas (0.5 mrem/hr < Dose Rate < 100 mrem/hr).
- Shields were located to give access to beam lines for maintenance.
- Major shield efforts were identified early on, to help obtain resource requirements.
- Approvals were given to shield designs deemed safe. The pre-approval process expedited formal review and release of drawings, and enabled parallel purchasing and fabrication.

Machine Design, Fabrication and Installation

Designs were created by generating LSDCG defined trace lines directly onto sketch planes of 3D lattice models. LSDCG verified location, size, frame construction, and material overlap. The models were detailed and 2D part and assembly drawings were generated and approved.

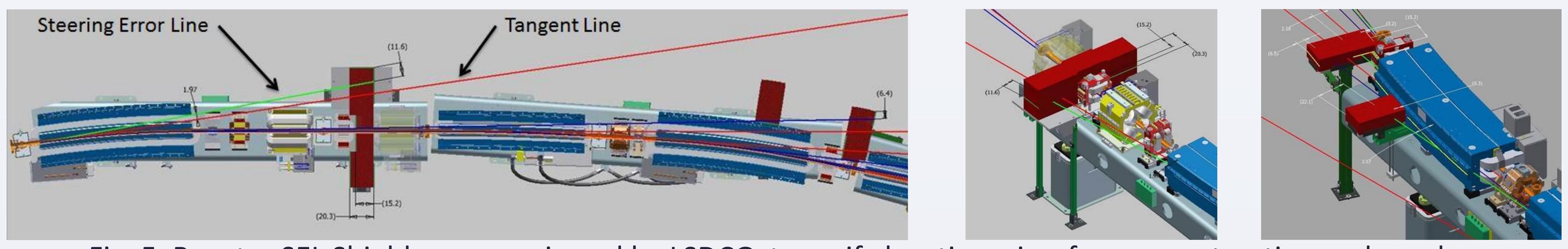
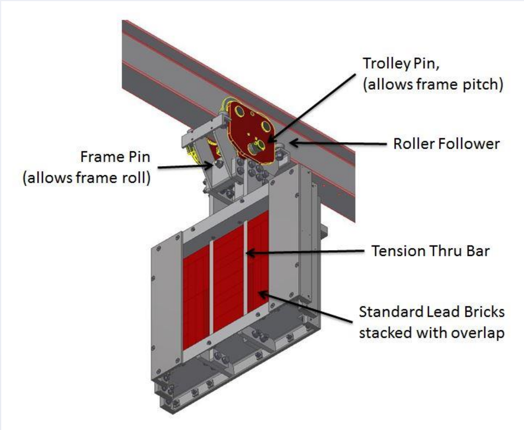
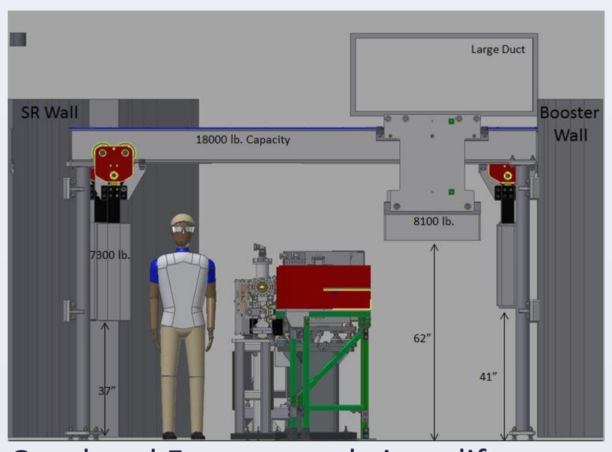


Fig. 5. Booster SEL Shields were reviewed by LSDCG, to verify location, size, frame construction and overlap.

Some support frames were custom designed to carry and move heavy loads. The Injection Straight was shielded with such frames, and its design required careful planning and application of classic strength of material principles. The shield frames are pinned to geared trolleys, which are mounted on overhead I-beams. Frames were loaded with lead, the heaviest at 7300 lb. Maximum bending and shear stress of pins were calculated, multiplied by a service factor and compared to material yield strength in shear. Test pins were loaded to design value with service factor, to guarantee safety. Lifting and pinning of frame was carefully handled by Brookhaven National Laboratory's hoist and rigging group.

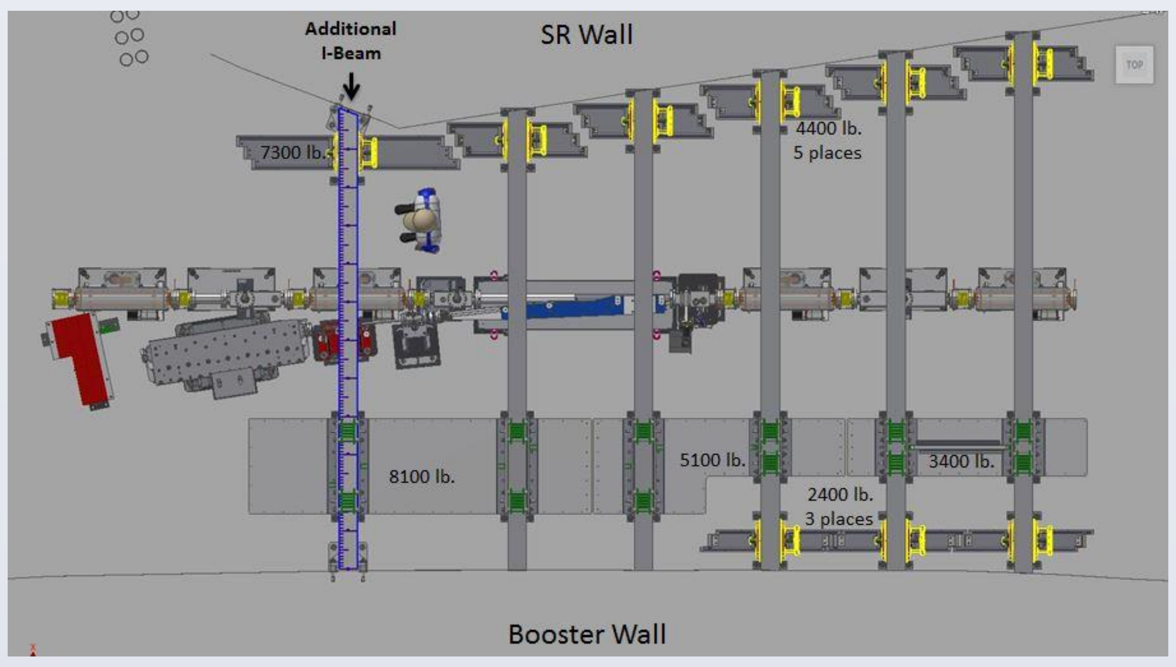


Side Shield Compartment Frame

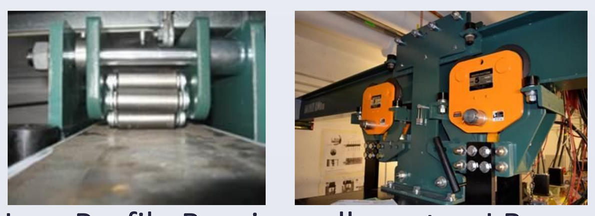


Overhead Frame travel gives lift access

Additional I Beam installed upstream



Injection Straight Shields retract for beam line access and service



Low Profile Bearing rolls on top I Beam

Frames lifted and pinned to trolleys

Fig. 6. The design of Storage Ring SEL Injection Shields was carefully planned for safe installation

All local shields are installed with approved assembly drawings and travelers. Most shield support frames were built from structural channels, where loads were verified against catalogued maximum load tables, for quick design. The shield material assembly drawings included multiple views of stacking and overlap requirements. A traveler is used to confirm the installation, so all requirements on the drawing are verified, including taking photos of multiple stacks, and measuring stack size and the installed distance from the beam line components.

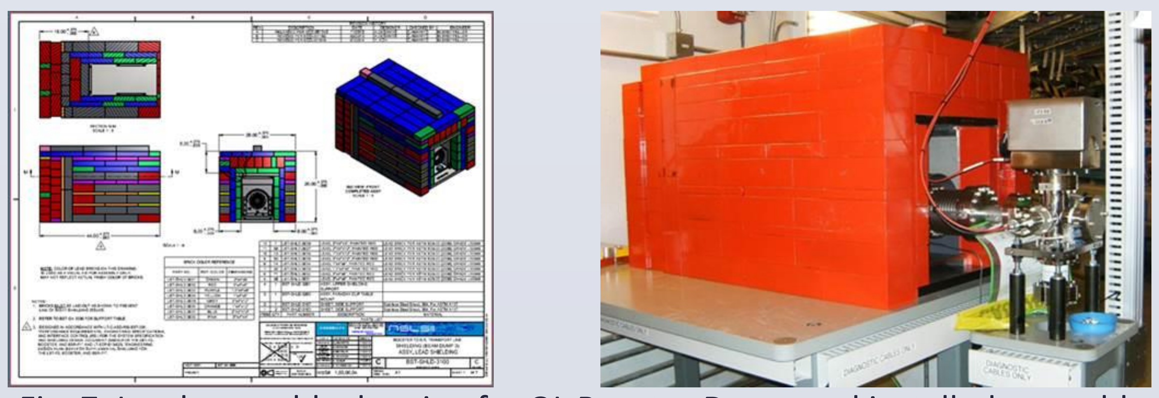


Fig. 7. Lead assembly drawing for OL Booster Dump and installed assembly

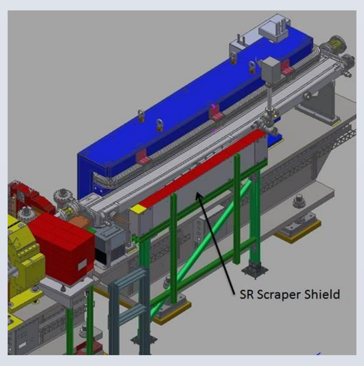
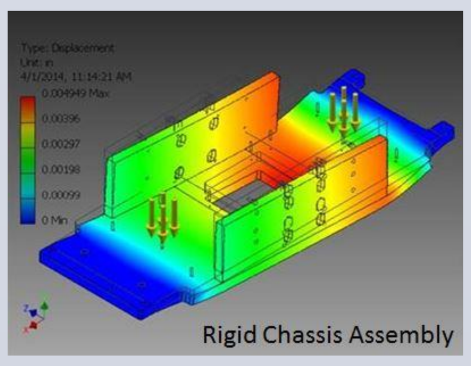


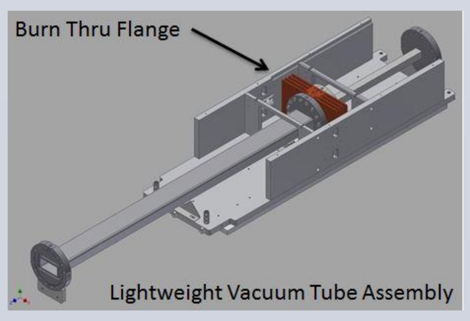
Fig. 8. BSL Scraper shield, mounted on structural frame

Ratchet Wall Collimator - A Challenging Shield Configuration

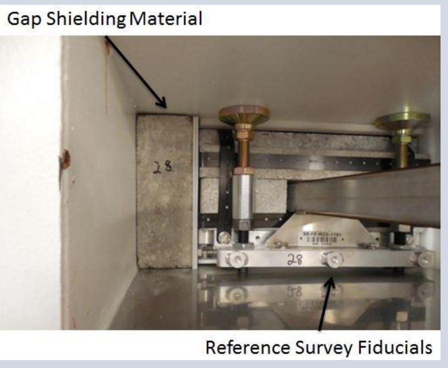
The RCO is installed in the ratchet wall penetration and shields the First Optics Enclosure from Insertion Device Bremsstrahlung and Storage Ring scatter radiation. Problems and solutions are discussed.

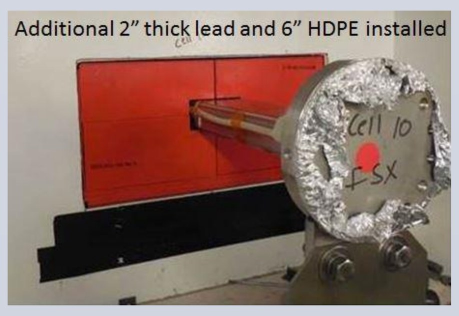
Fig. 9. RCO Assembly prepared for transport to I.D. penetration, where its installed behind ratchet lead.





- Assembly of collimator bricks in penetration impossible. – A rigid chassis was designed for precise tube and brick alignment that enabled the careful transport of the 550 lb. loaded RCO.
- Bake-out temperatures cause expansion and distortion. - Conditions were tested on chassis and the flange fiducials were measured to meet ±200µ aperture location specification.
- Extreme penetration sleeve location variation and skew. – A lightweight model was installed for measurements to select and modify materials.
- No visibility of Burn Thru Flange. – Fiducials were added to chassis and a reference survey file was created to enable critical positioning of the aperture during installation.





Acknowledgements:

The following people contributed a great amount of time and effort with their knowledge, creative thoughts, and hard work to successfully shield NSLS II from harmful radiation:

Ed Cheswick, Michael Johanson, Ben Rose, Bob Scheuerer, Stephen Sherwood and Brian Walsh.

References

[1] P.K. Job and W.R. Casey, "Preliminary Radiological Considerations for the Design and Operation of NSLS II Linac", Technical Note 12, July 2006.

[2] S.L. Kramer, R. Fliller, Y. Li, P.K. Job, NSLS-II Technical Note 101, "Local Radiation Shielding Design Methodology", Feb. 2013.